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General palladium-catalyzed cross coupling of cyclopropenyl esters†

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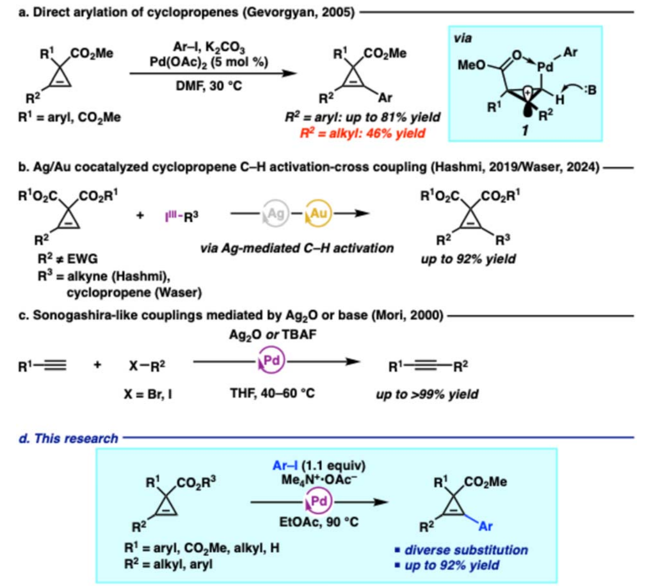
We report a method for the direct palladium-catalyzed cross coupling reactions of cyclopropenyl esters bearing a variety of substitution patterns with Csp^2 iodides. This reaction is largely insensitive to the electronic nature of the coupling partner. Tetramethylammonium acetate, a halide sequestrant, was exceptionally effective as an organic base. An observed KIE of 2.5 revealed C–H bond cleavage to be involved in the turnover-limiting step. This method enables the rapid assembly of cyclopropenes whose preparation previously required the use of toxic tin and arsenic reagents.

Our group has developed and utilized cyclopropene carbometallation reactions as the basis for various synthetic methods.[1,2] These applications necessitate modular methods to synthesize cyclopropenyl esters with fully substituted olefins in high yields. Generally, Stille coupling has been used to prepare these substrates,[3–5] but the required trialkyltin reagents and arsine ligands are highly toxic and Stille couplings of certain cyclopropenyl esters are sluggish and low-yielding.[2b,c] An ideal cross coupling of cyclopropenyl esters would proceed directly *via* formal C–H functionalization, obviating the use of toxic tin reagents and decreasing the synthetic step count. It is also essential that such a reaction would have high functional group tolerance.

The cyclopropene ring, with ∼54 kcal mol^{-1} of strain energy,[6] is primed to undergo numerous chemical reactions involving π bond breakage. Outside of synthetic methods developed by our group[7] and others,[8,9] cyclopropenes are commonly used as intermediates in total synthesis,[10] monomers in polymer chemistry,[11] and precursors to vinylcarbene intermediates.[12] In nature, cyclopropenes occur in certain toxic fatty acids.[13]

A direct Pd-catalyzed cross coupling of cyclopropenyl esters was reported by Gevorgyan in 2005 (Scheme 1a).[14] This excellent method enables the arylation of trisubstituted cyclopropenes bearing aryl substituents in moderate to high yields. However, an alkyl-substituted substrate underwent the reaction in only 46% yield, and the use of starting materials bearing fewer than three ring substituents was not reported. A series of mechanistic experiments indicated that the reaction likely proceeds *via* coordination of the cyclopropene to a palladium species to form complex **1**, which bears carbocationic character, and a fast deprotonation leads to a cyclopropenylpalladium species that can go on to afford the cross-coupling product. Substrates bearing alkyl substituents (R^2), which do not stabilize positive charge as effectively as aryl substituents, would therefore not undergo the reaction as efficiently.

In 2019, Hashmi reported a Ag/Au-cocatalyzed alkynylation of cyclopropenes which proceeds *via* Ag-mediated C–H activation (Scheme 1b).[15] A similar catalytic system was recently used by Waser to synthesize cyclopropene heterodimers.[16] These powerful methodologies were used to synthesize a wide array of privileged products, but *gem*-diester-containing cyclopropenes are required for high yields, and electron-withdrawing olefinic substituents are not tolerated. Cyclopropene alkynylation, as



Scheme 1 Relevant background and introduction to this research.

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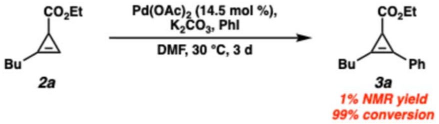


Scheme 2 Reported conditions do not effect the direct arylation of cyclopropene **2a**.

well as allylation, were also demonstrated by Xie using a dinuclear gold catalyst.[17]

If cyclopropenes are considered to be analogous to alkynes (based on hybridization[18] and reactivity), utilizing Ag-mediated C–H activation to activate cyclopropenes for Pd-catalyzed cross coupling would be analogous to Ag-promoted formal Sonogashira couplings. Mori reported that reactions resembling the Sonogashira coupling can be promoted in high yield by either Ag_2O or ionic bases like TBAF (Scheme 1c),[19] and Pale reported similar reactions with cocatalytic silver halides.[20]

Based on this precedent, we have succeeded in developing a general, direct cross-coupling of di- and trisubstituted cyclopropenyl esters with aryl and styrenyl iodides (Scheme 1d).

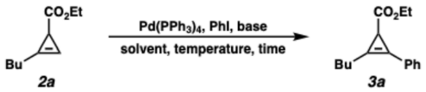
Disubstituted cyclopropenyl ester **2a**, prepared by Rh-catalyzed cyclopropenation,[21] was identified as an ideal model substrate due to challenges previously encountered with the derivatization of this substrate by stannylation and Stille coupling. We first subjected **2a** to Gevorgyan's direct cross coupling conditions with PhI[14] but observed only a trace of the desired product **3a** with nonspecific decomposition of the starting material (Scheme 2).

We then set out to identify reaction conditions that would effect the cross coupling of cyclopropene **2a** with PhI (Table 1). Based on the hypothesis that silver-mediated C–H activation could enable a Sonogashira-type mechanism, the AgI-cocatalyzed conditions demonstrated by Pale for alkyne coupling were tested (entries 1 and 2), but desired product **3a** was not detected.[20] However, employing stoichiometric AgOAc as a base afforded 39% of the desired product (entry 3). Switching to Ag_2O-mediated conditions based on those reported by Mori led to a high yield of **3a** in just 2 hours at 70 °C (entry 4). The reaction proceeded slowly at ambient temperature (entry 5). Based on the precedent of Mori, we envisioned that a base-mediated reaction should be possible and would obviate the use of (super)stoichiometric silver. While several bases tested did promote formation of **3a** (entries 6–8), these reactions were sluggish and proceeded with poor mass recovery. We therefore hypothesized that Ag is necessary to promote cross coupling by iodide abstraction from a Pd intermediate.[22] An alternative halide sequestrant could obviate the use of stoichiometric silver. While most candidates (*i.e.* Pb and Tl salts) present a safety and environmental hazard, Larrosa demonstrated the use of tetramethylammonium acetate as an iodide sequestrant in Pd-catalyzed C–H activation,[23] and a related application has since been explored on a process scale.[24]

Conducting the arylation of **2a** with Me_4NOAc as the base in the presence of AgI led to a promising level of conversion and high mass recovery (entry 9). In the higher boiling and green solvent EtOAc, reaction at 90 °C afforded complete conversion of **2a** and 85% yield in 17 h (entry 10). Me_4NOAc was confirmed to be uniquely effective (entry 11), and furthermore, AgI does not play a catalytic role (entry 12). Indeed, a control experiment (see ESI†) revealed that Ag_2O does not independently effect C–H activation of cyclopropene **2a**. The reaction proceeded with a decreased catalyst loading, albeit in diminished yield (entry 13).

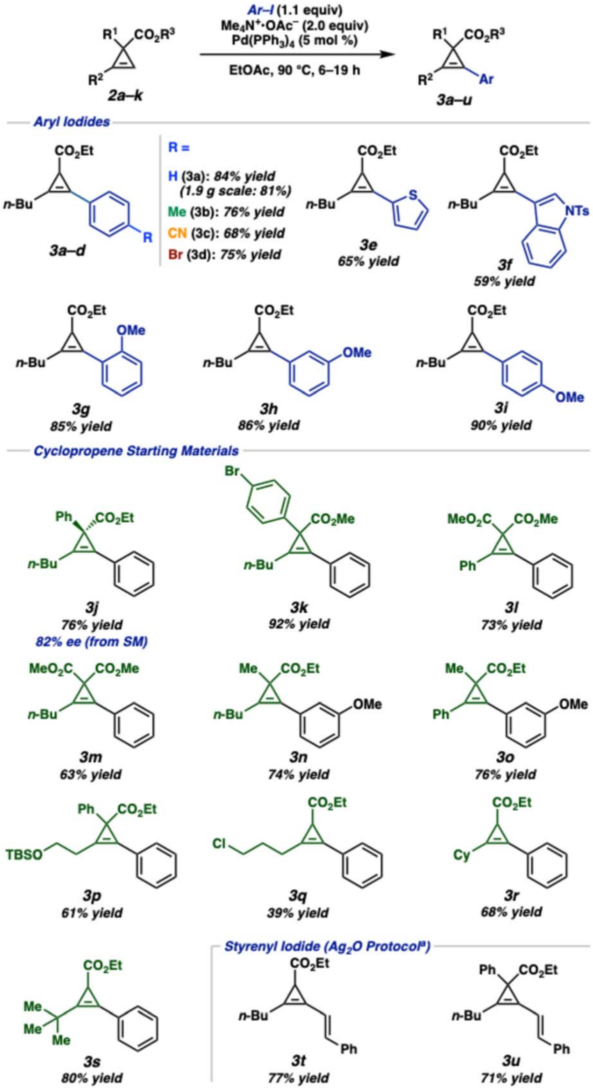
However, upon encountering reproducibility problems at lower catalyst loadings, we opted to explore the substrate scope using 5% Pd.

Table 1 Optimization of reaction conditions[a]



Entry	Catalyst loading	Base	Additive	Solvent	Temperature	Time	% SM	% Yield
1	14.5 mol%	DIPEA	AgI (29 mol%)	DMF	23 °C	17 h	n.d.	—
2	14.5 mol%	DIPEA	AgI (29 mol%)	THF	70 °C	17 h	n.d.	—
3	7.2 mol%	AgOAc	—	THF	70 °C	18 h	—	39%
4	7.2 mol%	Ag_2O	—	THF	70 °C	2 h	—	84%
5	7.2 mol%	Ag_2O	—	THF	23 °C	18 h	51%	28%
6	7.2 mol%	TBAF	—	THF	70 °C	21 h	42%	22%
7	7.2 mol%	KOPh	—	THF	70 °C	16 h	20%	33%
8	7.2 mol%	CsOAc	—	THF	70 °C	17 h	23%	20%
9	7.2 mol%	Me_4NOAc	AgI (29 mol%)	THF	70 °C	16 h	19%	68%
10	5.7 mol%	Me_4NOAc	AgI (29 mol%)	EtOAc	90 °C	17 h	—	85%
11	5.7 mol%	TBAOAc	AgI (29 mol%)	EtOAc	90 °C	17 h	—	51%
12	**5.7 mol%**	**Me_4NOAc**	—	**EtOAc**	**90 °C**	**19 h**	—	**86%**
13	1.1 mol%	Me_4NOAc	—	EtOAc	90 °C	15 h	—	77%

[a] Reactions were conducted on a 0.2–0.3 mmol scale and yields were determined by ^1H NMR analysis using 1,3,5-trimethoxybenzene as an internal standard.



Scheme 3 Substrate scope. All reactions were conducted on a 0.5 mmol scale at 0.25 M concentration unless otherwise noted. [a]Conducted at 0.1 M concentration in THF at 50 °C for 20 h using 1 equiv. Ag_2O instead of Me_4NOAc.

A variety of aryl iodides were suitable for cross-coupling with cyclopropene **2a** in moderate to high yields (Scheme 3). Phenyl product **3a** was prepared on a 1.9 g (10 mmol) scale without a significant drop in yield. Products bearing electron-donating (**3b**, **3i**) and electron-withdrawing substituents (**3c**, **3h**) could be furnished, and an aryl bromide (**3d**) did not interfere with the reaction, demonstrating high chemoselectivity toward aryl iodides. 2-Iodothiophene and an iodoindole were also suitable coupling partners (**3e**, **3f**). Notably, *ortho*-iodoanisole provided product **3g** in high yield despite potential steric clash.

Cyclopropene starting materials bearing a variety of substitution patterns were competent substrates in this reaction. An enantioenriched trisubstituted cyclopropene prepared by the method of Davies afforded optically active product **3j**.[25] A *p*-bromophenyl group was tolerated in a similar substrate (**3k**). Remarkably, cyclopropenes bearing *gem*-diester moieties (**3l**, **3m**) underwent the cross-coupling smoothly without ring fragmentation.[26] Similarly, fully substituted cyclopropenes with methyl-substituted quaternary centers (**3n**, **3o**) were obtained in high yields. The reaction is also relatively insensitive to the nature of the olefinic substituent. A tethered silyloxy group (**3p**) and alkyl chloride (**3q**) were tolerated, albeit with some loss of yield to side reactions. Secondary and tertiary alkyl-substituted products were formed in moderate to high yields (**3r**, **3s**).

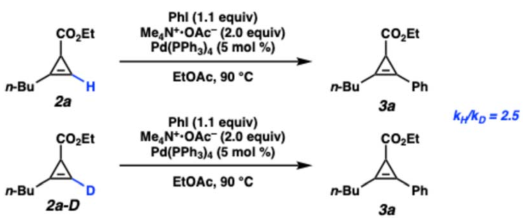
This method was also applied to the alkenylation of cyclopropenes. However, in this case, milder reaction conditions were necessary due to product instability. Ag_2O-mediated conditions derived from those evaluated during the initial reaction optimization (Table 1, entry 4) provided diene products **3t** and **3u** in 77% and 71% yields, respectively. For substrates and electrophiles that did not undergo the desired reaction, see the ESI.†

To interrogate the mechanism of this cross-coupling, the deuterium kinetic isotope effect for the reaction was measured by preparing deuterated cyclopropene **2a-D** and conducting two reactions in parallel (Scheme 4). A primary KIE ($k_H/k_D = 2.5$) was observed, indicating that C–H bond cleavage occurs in the turnover-limiting step of the reaction.[27] This is in contrast to the related reaction studied by Gevorgyan,[14] which exhibited a k_H/k_D value of 1.0.

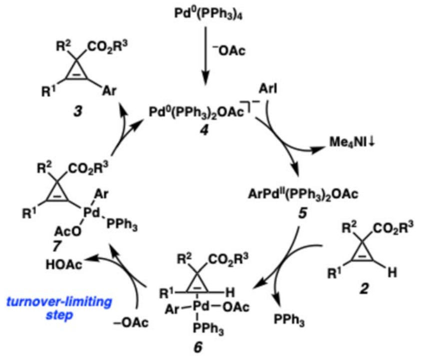
On the basis of this result and literature precedent, we propose a catalytic cycle for the reported reaction (Scheme 5). An anionic Pd(0) species **4** would engage in oxidative addition with aryl iodide to provide Pd(II) acetate complex **5**, following iodide sequestration. The latter complex could coordinate to a cyclopropene **2**, leading to complex **6**. Then, turnover-limiting deprotonation would afford cyclopropenyl complex **7**, which could undergo reductive elimination to release product **3** and complete the catalytic cycle (Scheme 6).

Solutions of $Pd(PPh_3)_4$ containing acetate have been shown to transiently form anionic complex **4**, which is responsible for oxidative addition.[28] Amatore found that ligand substitution of iodide with acetate is necessary for $PhPdI(PPh_3)_2$ to react with styrene *via* migratory insertion. While in the present case migratory insertion does not occur, as evidenced by the lack of formation of Heck-type methylenecyclopropane products when R^1 = alkyl, iodide sequestration is likely necessary to favor formation of acetate complex **5** and enable coordination of **2** to the palladium center.

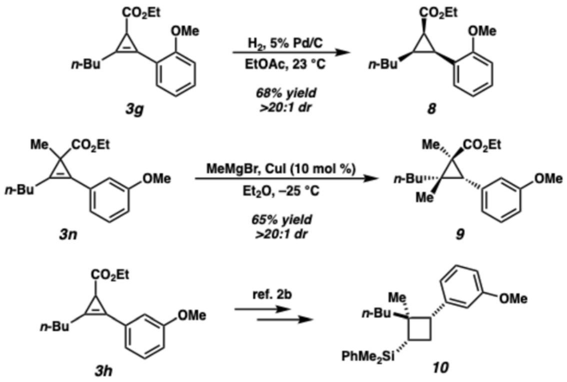
The subsequent step, deprotonation of the substrate and formation of cyclopropenyl palladium species **7**, is turnover-limiting as evidenced by the observed KIE. While we cannot definitively rule out an intramolecular concerted metallation-



Scheme 4 Kinetic isotope effect experiment.



Scheme 5 Proposed catalytic cycle.



Scheme 6 Utility of products reported herein.

deprotonation (CMD) mechanism involving a palladium-coordinated acetate ligand, the competence of fluoride and phenoxide bases (see Table 1, entries 6, 7) and the lack of a significant rate acceleration in the presence of acetate suggest an intermolecular deprotonation event akin to the step proposed by Gevorgyan[14] or similar processes in Cu-free Sonogashira-type couplings.[29]

The products generated by the method reported herein possess synthetic utility. For example, hydrogenation of cyclopropene **3g** over Pd/C afforded all-*cis* cyclopropane **8**. Cu-catalyzed diastereoselective carbometallation[2c] of cyclopropene **3n** yielded pentasubstituted cyclopropane **9** with excellent diastereoselectivity. Anisole derivative **3h** was recently advanced to cyclobutane **10** *via* the formation of a bicyclo[1.1.0]butane intermediate.[2b]

Conclusions

A method for the direct cross-coupling of cyclopropenyl esters was developed, enabled by the use of tetramethylammonium acetate as a halide sequestrant. This method is suitable for the arylation of cyclopropenyl esters bearing a variety of substitution patterns, and alkenylation was demonstrated under silver-mediated conditions. This reaction provides an improved method for the synthesis of a variety of strained synthetic building blocks.

Data availability

The data supporting this article have been included as part of the ESI.†

Author contributions

Z. P. S. conceived of the project, performed experiments, analyzed data, and wrote the manuscript. I. M. supervised the project, obtained funding, and edited the manuscript.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

1 Y. Cohen and I. Marek, Regio- and Diastereoselective Carbometalation Reaction of Cyclopropenes, *Acc. Chem. Res.*, 2022, **55**, 2848–2868.

2 (*a*) R. Suresh, N. Orbach and I. Marek, Synthesis of Stereodefined Polysubstituted Bicyclo[1.1.0]butanes, *J. Am. Chem. Soc.*, 2024, **146**, 13748–13753; (*b*) Z. P. Sercel and I. Marek, Access to Quaternary-Substituted Cyclobutylsilanes by Ring Opening of Arylbicyclobutanes with Silyllithium Reagents, *Angew. Chem., Int. Ed.*, 2025, **64**, e202421235; (*c*) Y. Cohen, A. U. Augustin, L. Levy, P. G. Jones, D. B. Werz and I. Marek, Regio- and Diastereoselective Copper-Catalyzed Carbomagnesiation for the Synthesis of Penta- and Hexa-Substituted Cyclopropanes, *Angew. Chem., Int. Ed.*, 2021, **60**, 11804–11808.

3 S. Untiedt and A. de Meijere, Pd(0)-Catalysed Coupling of Cyclopropenylzinc Chlorides and Cyclopropenylstannanes – A New Efficient Synthesis of 1-Phenyl-, 1-Ethenyl-, and 1-Ethynyl-1-cyclopropenes, *Chem. Ber.*, 1994, **127**, 1511–1515.

4 E. A. F. Fordyce, T. Luebbers and H. W. Lam, Synthesis and Application of Alkenylstannanes Derived from Base-Sensitive Cyclopropenes, *Org. Lett.*, 2008, **10**, 3993–3996.

5 Alkenyl and alkynyl derivatives are accessible by Au-catalyzed cross coupling: X. Li, M. D. Wodrich and J. Waser, *Nat. Chem.*, 2024, **16**, 901–912.

6 R. D. Bach and O. Dmitrenko, Strain Energy of Small Ring Hydrocarbons. Influence of C-H Bond Dissociation Energies, *J. Am. Chem. Soc.*, 2004, **126**, 4444–4452.

7 Representative examples: (*a*) H. Sommer and I. Marek, Diastereo- and Enantioselective Copper Catalyzed Hydroallylation of Disubstituted Cyclopropenes, *Chem. Sci.*, 2018, **9**, 6503–6508; (*b*) T. Weissbrod, A. Asraf and

I. Marek, Copper-Catalyzed Carbomagnesiation of 1-Halocyclopropenes, *Org. Lett.*, 2024, **26**, 9138–9141; (*c*) V. Myronova, D. Cahard and I. Marek, Stereoselective Preparation of CF_3-Containing Cyclopropanes, *Org. Lett.*, 2022, **24**, 9076–9080.

8 Representative examples: (*a*) X. Xie, Y. Li and J. M. Fox, Selective Syntheses of $\Delta^{\alpha,\beta}$ and $\Delta^{\beta,\gamma}$ Butenolides from Allylic Cyclopropenecarboxylates *via* Tandem Ring Expansion/[3,3]-Sigmatropic Rearrangements, *Org. Lett.*, 2013, **15**, 1500–1503; (*b*) V. Tarwade, X. Liu, N. Yan and J. M. Fox, Directed Carbozincation Reactions of Cyclopropene Derivatives, *J. Am. Chem. Soc.*, 2009, **131**, 5382–5383; (*c*) V. Tarwade, R. Selvaraj and J. M. Fox, Facially Selective Cu-Catalyzed Carbozincation of Cyclopropenes Using Arylzinc Reagents Formed by Sequential I/Mg/Zn Exchange, *J. Org. Chem.*, 2012, **77**, 9900–9904; (*d*) N. Yan, X. Liu and J. M. Fox, Facially Selective and Regioselective Carbometalation of Cyclopropenes by Aryl Grignard Reagents, *J. Org. Chem.*, 2008, **73**, 563–568; (*e*) A. Parra, L. Amenós, M. Guisán-Ceinos, A. López, J. L. G. Ruano and M. Tortosa, Copper-Catalyzed Diastereo- and Enantioselective Desymmetrization of Cyclopropenes: Synthesis of Cyclopropylboronates, *J. Am. Chem. Soc.*, 2014, **136**, 15833–15836; (*f*) A. Trofimov, M. Rubina, M. Rubin and V. Gevorgyan, Highly Diastereo- and Regioselective Transition Metal-Catalyzed Additions of Metal Hydrides and Bimetallic Species to Cyclopropenes: Easy Access to Multisubstituted Cyclopropanes, *J. Org. Chem.*, 2007, **72**, 8910–8920; (*g*) A. T. Stoll and E. Negishi, A mild and selective synthesis of cyclopropene and cyclopropane derivatives *via* cycliallylation of alkenyllithiums, *Tetrahedron Lett.*, 1985, **26**, 5671–5674; (*h*) S. Nie, A. Lu, E. L. Kuker and V. M. Dong, Enantioselective Hydrothiolation: Diverging Cyclopropenes through Ligand Control, *J. Am. Chem. Soc.*, 2021, **143**, 6176–6184; (*i*) M. Wang, J. C. Simon, M. Xu, S. A. Corio, J. S. Hirschi and V. M. Dong, Copper-Catalyzed Hydroamination: Enantioselective Addition of Pyrazoles to Cyclopropenes, *J. Am. Chem. Soc.*, 2023, **145**, 14573–14580; (*j*) B. S. Daniels, X. Hou, S. A. Corio, L. M. Weissman, V. M. Dong, J. S. Hirschi and S. Nie, Copper-Phosphido Catalysis: Enantioselective Addition of Phosphines to Cyclopropenes, *Angew. Chem., Int. Ed.*, 2023, **62**, e202306511.

9 Recent review: B. P. Raiguru, S. Nayak, D. R. Mishra, T. Das, S. Mohapatra and N. P. Mishra, *Asian J. Org. Chem.*, 2020, **9**, 1088–1132.

10 Representative examples: (*a*) X.-T. Liang, J.-H. Chen and Z. Yang, Asymmetric Total Synthesis of (−)-Spirochensilide A, *J. Am. Chem. Soc.*, 2020, **142**, 8116–8121; (*b*) E. Z. Oblak, M. D. VanHeyst, J. Li, A. J. Wiemer and D. L. Wright, Cyclopropene Cycloadditions with Annulated Furans: Total Synthesis of (+)- and (−)-Frondosin B and (+)-Frondosin A, *J. Am. Chem. Soc.*, 2014, **136**, 4309–4315.

11 B. R. Elling, J. K. Su and Y. Xia, Polymerization of Cyclopropenes: Taming the Strain for the Synthesis of Controlled and Sequence-Regulated Polymers, *Acc. Chem. Res.*, 2021, **54**, 356–365.

12 M. Rubin, M. Rubina and V. Gevorgyan, Transition Metal Chemistry of Cyclopropenes and Cyclopropanes, *Chem. Rev.*, 2007, **107**, 3117–3179.

13 T. L. Wilson, C. R. Smith Jr and K. L. Mikolajczak, Characterization of cyclopropenoid acids in selected seed oils, *J. Am. Oil Chem. Soc.*, 1961, **38**, 696–699.

14 S. Chuprakov, M. Rubin and V. Gevorgyan, Direct Palladium-Catalyzed Arylation of Cyclopropenes, *J. Am. Chem. Soc.*, 2005, **127**, 3714–3715.

15 Y. Yang, P. Antoni, M. Zimmer, K. Sekine, F. F. Mulks, L. Hu, L. Zhang, M. Rudolph, F. Rominger and A. S. K. Hashmi, Dual Gold/Silver Catalysis Involving Alkynylgold(III) Intermediates Formed by Oxidative Addition and Silver-Catalyzed C–H Activation for the Direct Alkynylation of Cyclopropenes, *Angew. Chem., Int. Ed.*, 2019, **58**, 5129–5133.

16 X. Li and J. Waser, Forging 1,1′-Bicyclopropenyls by Synergistic Au/Ag Dual-Catalyzed Cyclopropenyl Cross-Coupling, *J. Am. Chem. Soc.*, 2024, **146**, 29712–29719.

17 K. Liu, T. Li, D.-Y. Liu, W. Li, J. Han, C. Zhu and J. Xie, Dinuclear gold-catalyzed C–H bond functionalization of cyclopropenes, *Sci. China: Chem.*, 2021, **64**, 1958–1963.

18 F. H. Allen, The geometry of small rings—IV: Molecular geometry of cyclopropene and its derivatives, *Tetrahedron*, 1982, **38**, 645–655.

19 A. Mori, J. Kawashima, T. Shimada, M. Suguro, K. Hirabayashi and Y. Nishihara, Non-Sonogashira-Type Palladium-Catalyzed Coupling Reactions of Terminal Alkynes Assisted by Silver(I) Oxide or Tetrabutylammonium Fluoride, *Org. Lett.*, 2000, **2**, 2935–2937.

20 U. Létinois-Halbes, P. Pale and S. Berger, Ag NMR as a Tool for Mechanistic Studies of Ag-Catalyzed Reactions: Evidence for *in Situ* Formation of Alkyn-1-yl Silver from Alkynes and Silver Salts, *J. Org. Chem.*, 2005, **70**, 9185–9190.

21 N. Petiniot, A. J. Anciaux, A. F. Noels, A. J. Hubert and P. Teyssié, Rhodium catalysed cyclopropenation of acetylenes, *Tetrahedron Lett.*, 1978, **19**, 1239–1242.

22 T. Bhattacharya, S. Dutta and D. Maiti, Deciphering the Role of Silver in Palladium-Catalyzed C−H Functionalizations, *ACS Catal.*, 2021, **11**, 9702–9714.

23 C. Arroniz, J. G. Denis, A. Ironmonger, G. Rassias and I. Larrosa, An organic cation as a silver(I) analogue for the arylation of sp2 and sp3 C–H bonds with iodoarenes, *Chem. Sci.*, 2014, **5**, 3509–3514.

24 C. Hang, A. Ramirez, C. Chan, Y. Hsiao, A. J. DelMonte and E. M. Simmons, Mechanistic Studies of a Pd-Catalyzed Direct Arylation En Route to Beclabuvir: Dual Role of a Tetramethylammonium Cation and an Unusual Turnover-Limiting Step, *ACS Catal.*, 2021, **11**, 2460–2472.

25 H. M. L. Davies and G. H. Lee, Dirhodium(II) Tetra(*N*-(dodecylbenzenesulfonyl)prolinate) Catalyzed Enantioselective Cyclopropenation of Alkynes, *Org. Lett.*, 2004, **6**, 1233–1236.

26 Representative examples:(*a*) J. Chen and S. Ma, Catalyst-Controlled Ring-Opening Cycloisomerization Reactions of Cyclopropenyl Carboxylates for Highly Regioselective

Synthesis of Different 2-Alkoxyfurans, *Chem.–Asian J.*, 2010, **5**, 2415–2421; (*b*) S. Ma, J. Zhang, Y. Cai and L. Lu, An X^- (X = I, Br)-Triggered Ring-Opening Coupling Reaction of Cyclopropenes with Organic Halides, *J. Am. Chem. Soc.*, 2003, **125**, 13954–13955; (*c*) Y. Liu and S. Ma, Unique reactivity of Grignard reagents towards cyclopropenylcarboxylates—highly selective carbon–carbon bond cleavage, *Chem. Sci.*, 2011, **2**, 811–814.

27 E. M. Simmons and J. F. Hartwig, On the Interpretation of Deuterium Kinetic Isotope Effects in C–H Bond Functionalizations by Transition-Metal Complexes, *Angew. Chem., Int. Ed.*, 2012, **51**, 3066–3072.

28 C. Amatore and A. Jutand, Anionic Pd(0) and Pd(II) Intermediates in Palladium-Catalyzed Heck and Cross-Coupling Reactions, *Acc. Chem. Res.*, 2000, **33**, 314–321.

29 C. Palladino, T. Fantoni, L. Ferrazzano, B. Muzzi, A. Ricci, A. Tolomelli and W. Cabri, New Mechanistic Insights into the Copper-Free Heck–Cassar–Sonogashira Cross-Coupling Reaction, *ACS Catal.*, 2023, **13**, 12048–12061.